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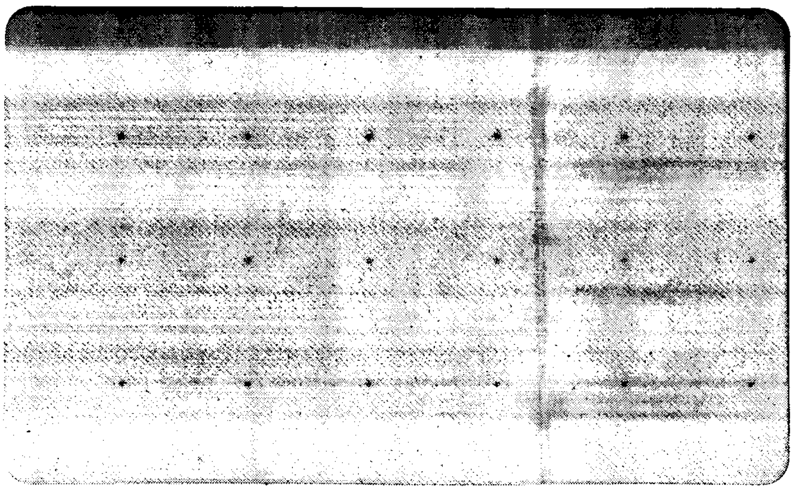

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ACTIVE REGION PLAGES

AND THE HYADES ANOMALY

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ABSTRACT

Crawford, Campbell, and Rose each have shown that the Hyades do not obey the color-color relations and spectral properties exhibited by nearby field stars. We show that all such anomalies of the Hyades are caused by excess emission from magnetic regions (plages) on the surfaces of these cluster stars. The Pleiades stars and a few extreme emission stars show similar effects, but of such magnitude to indicate that plages on Pleiades stars have higher surface brightnesses than the Sun and do not merely cover a larger fraction of the stars.

Key words: stellar activity, Hyades

Short title: Hyades Anomaly

I. INTRODUCTION

Crawford (1969) and Stromgren, Olsen, and Gustafsson (1982) have demonstrated that the Hyades main-sequence stars of spectral type F are anomalous relative to field dwarfs in the Stromgren (uvby) photometric system; for a given b-y, the Hyades dwarfs show a c_1 excess of ~0.035 mag relative to field stars of the same metallicity. Taken at face value, the excess, known as the "Hyades anomaly," indicates a lower surface gravity for the Hyades that could be explained if their helium abundance were 0.06 (by number) lower than for field stars (Stromgren et al. 1982). This explanation would have serious consequences for Big Bang nucleosynthesis. Recently, Campbell (1984) has also found a color anomaly in Hyades (and Pleiades) dwarfs, in that for a given V-K they are bluer in B-V than field dwarfs of the same metal abundance. He concludes that the Hyades and Pleiades stars are heavily spotted relative to the field stars and that their colors are noticeably affected by the cool spots. In fact, he proposes that the presence of starspots inflates the Hyades stars, resulting in a lowering of their surface gravity (at a given temperature) by just the amount indicated by the "Hyades anomaly." There has long been evidence to support Campbell's assertion of solar-like activity on the Hyades dwarfs. Wilson (1963) found that the mean Ca II K emission reversal, and by inference the level of chromospheric activity, in the Hyades (and Pleiades) is higher than that in the average field stars. Recently, Cayrel et al. (1983) found that two solar temperature Hyades dwarfs have Hα emission cores and that their Ca II λ8469 and λ8542 lines are partially filled in relation to the Sun, a phenomenon they attribute to chromospheric activity. Finally, Rose (1984) has found numerous spectral anomalies in the Hyades, Pleiades, and field stars with Ca II K emission reversals; he also attributes these anomalies to surface activity.

In this paper we demonstrate on the basis of observations of solar plages that all color and spectral anomalies in the Hyades and Pleiades, including the original Hyades anomaly, are the result of active regions on the surfaces of the stars. In moderate cases (e.g., the Hyades), the anomalies can be explained strictly in terms of the effect of magnetic plages. In the more extreme cases (the Pleiades), there is evidence that plages are intrinsically brighter than solar plages and do not merely cover a larger fraction of the star.

II. OBSERVATIONS

Rose (1984) has defined a system for quantifying spectral classification based on spectra in the region λ3500-4500 Å. Spectral indices were defined that ordinarily measure the temperature, surface gravity, and chemical composition of a star, but in the case of the Hyades and other active stars, most indices exhibit anomalous behavior. We have observed these particular spectral indices in a variety of solar plages and quiet regions for direct comparison with the stellar data.

A. The Solar Data

Solar data were taken with a 500 pixel vidicon detector on the coudé spectrograph at Mees Observatory on Haleakala, Maui (Landman 1980). Spectra of 32 pairs of magnetic and nonmagnetic regions near the center of the disk were obtained over 5 different observing runs. The spectra have a dispersion of 0.17 Å per pixel. Each region is 4 x 8 arcseconds in area and is observed over a 10 minute interval. Ca II H and K lines were observed for all regions, and Hα and Hβ for most regions, but Hγ and Hδ and the CN λ3883 Å features were observed in a minority of regions. The original spectra were dark subtracted, flat divided, straightened, and normalized to the local continuum peaks. For comparison with the stellar data, the spectra were convolved with a Gaussian of 2.5 Å width, and the intensity of line cores and continuum peaks measured over a 0.52 Å window.

As a measure of the chromospheric emission, a Ca II HK index was constructed from the unbroadened spectra. The intensities of 1 Å bands at the centers of the H and K lines were normalized by the mean intensities of two pseudo-continuum bands, one 5 Å wide centered at λ3913 Å, the other 4 Å wide at λ3989.5 Å. This HK index is comparable with the Mount Wilson S index (Vaughan, Preston, and Wilson 1978). Nonmagnetic regions have $0.16 < HK < 0.22$; magnetic regions have $0.22 < HK < 0.61$. The Sun is observed to have $S \simeq 0.20$, and the most active G stars have $S \simeq 0.5$ (Vaughan and Preston 1980). While the scales of S and HK are close, they may differ by a factor $\leq 20\%$.

B. The Stellar Data

Photographic spectra of 82 field dwarfs, 35 Hyades dwarfs, and 31 Pleiades dwarfs were obtained with the image intensifier and Cassegrain spectrograph of the University of Hawaii 2.2 m telescope at Mauna Kea Observatory. These data have been reported in a previous paper (Rose 1984). The spectra, which have a resolution of 2.5 Å, were calibrated to relative intensity, but no correction was made for the instrumental response or atmospheric extinction. Details of the observing and reduction procedures are given in Rose (1984). For this paper, spectra of the Sun were obtained from the asteroid 14 Irene on three occasions. In addition, the dwarf HD88725, for which only a single underexposed spectrum had been obtained by Rose (1984), was reobserved twice. Finally, a single spectrum was obtained for ADS2644A, a dwarf known to exhibit a high level of chromospheric activity (Wilson 1963).

The spectra are used to construct a three-dimensional quantitative spectral classification (Rose 1984). Spectral indices are formed by ratioing the intensities at (1) the cores of two spectral lines, or (2) at the peaks of two pseudo-continua. This method renders the indices insensitive to changes in wavelength resolution and errors in linearization of the photographic emulsion.

Because the local slope of the spectrum is not removed, the stellar and solar line ratios in a given region may differ by a multiplicative factor. The difference in scales is <10%, as one can see from comparison of the mean values in Table I (solar data) and Table II (stellar data, using the asteroid spectra). Note that there is a larger zero point difference between solar and stellar data in the case of the Hδ/Fe I index. This is because the solar data compare Hδ to Fe I λ4063, whereas the stellar data compare Hδ to the mean of Fe λ4063 and λ4045.

III. SPECTRAL INDICATORS IN PLAGES

A. Difference between Magnetic and Nonmagnetic Regions (plage vs quiet)

The temperature is higher at every height in a magnetic region than in a quiet region. The temperature difference increases with height. Spectral lines formed in LTE will show an emission excess in plages appropriate to their height of formation. Strong lines will be filled in by plage emission more than weak lines will.

B. Formation of the Balmer Lines

The Balmer lines have significant opacity deep in the photosphere, where the damping wings are formed, and in the chromosphere, where the cores are formed (Schoolman 1972). They receive little contribution from the upper photosphere and temperature minimum layers. In the chromosphere, the Balmer lines are not formed in LTE (Thomas 1957), because their line source functions are controlled by radiative processes, rather than collisional processes. Therefore their intensities are not simply related to the local temperature, and the higher Balmer lines show excess core absorption in plages, rather than the emission observed in the Ca II H, K, and IR-triplet lines (Title 1966). As one proceeds to more intense plages, the chromosphere becomes more effectively thick, and the collisional terms in the line source functions become larger compared to the radiative terms (i.e., the line excitation is more nearly in LTE). Hα is sufficiently collisionally excited in the chromosphere that it does couple to the temperature excess and does show plage emission. Hβ shows emission in very intense plages, but not in ordinary plages. In flares, the chromospheric temperature rise is pushed down in height to regions of higher density, and all Balmer lines may become coupled to the local temperature. Under flare conditions, the lines may not only weaken, but reverse into emission (Jefferies, Smith, and Smith 1959). Note that a flare is an episode of unusually high chromospheric heating, and thus illustrates the appearance the chromosphere would have if such higher heating level were possible in the steady state. We do not know a priori that plages on other stars are restricted to the same range of temperature excess as seen on the Sun. Other stars may have plages with higher heating rates than are seen in solar plages, that is, have plage Ca II emission HK > 0.6.

C. Balmer to Metal Line Ratios

Figure 1 shows the ratios of the Balmer lines to adjacent Fe I lines, as functions of the Ca II HK index. The variation in behavior of these ratios as one progresses from red to blue is basically caused by the decreasing chromospheric Balmer line excitation and increasing photospheric metal line opacity. The lines on the plots are based on the data of Table I.

The Hα/Fe I λ6593 ratio shows a steady increase for HK > 0.25. The Fe I line is weak and brightens only $\approx$0.5% in bright plages. Hα brightens steadily in plages, and the ratio has a total variation relative to the mean of $\approx$6%, the largest for any Balmer line.

The Hβ/Fe I λ4892 ratio mimics the Hα/Fe I behavior. However, the decreased chromospheric excitation causes the Hβ to delay its chromospheric brightening until HK > 0.4. The increasing Hβ opacity from HK $\approx$ 0.2 to 0.3 causes a slight decrease in the ratio. The total relative variation is $\approx$3%.

The Hγ/Fe I λ4325 ratio reflects the much lower Hγ chromospheric excitation and much stronger metal line. The Fe I line brightens by ~6% (relative) in the brightest plages. The increased Hγ chromospheric excitation in the hotter plages nearly balances the Hγ photospheric brightening, and the line ratio decreases. In plages with HK > 0.5, the Hγ chromosphere begins to brighten, and the Hγ/Fe I ratio stabilizes. At higher levels of HK, the ratio presumably increases, analogous to Hβ/Fe I. The total relative variation is $\approx$2%.

The Hδ/Fe I λ4063 ratio is virtually unaffected by the chromosphere. The Hδ chromospheric excitation is so low that one sees only a slight increase in Hδ/Fe I vs HK as the Hδ photospheric wings brighten faster than the Fe I line. The total relative variation is ≈2%. This ratio is our primary surface temperature indicator. The variation seen from quiet Sun to brightest plage corresponds to one-third of a decimal MK spectral class.

We expect that if regions with HK > 0.6 were observed, the Hγ and Hδ lines would eventually mimic the behavior of Hα and Hβ. Such regions are only found in flares on the Sun, but may occur in the steady-state in plages on other stars.

D. Other Line Ratios

The Hγ/G-band (λ4315) ratio is shown as a function of HK in Figure 2. Its behavior is similar to Hγ/Fe I (Fig. 1, lower left) but shows a larger range, ≈7%, since the G-band brightens more than Fe I λ4325. The Hγ/G-band ratio also appears to level out for HK > 0.5.

Figure 3 displays the ratios p(3912)/p(CN) and λ3886/λ3859 as functions of HK. Here, p( ) implies a pseudo-continuum peak is measured, and p(CN) is the sum of peaks at λ3852, 3864, and 3876 Å. These CN-sensitive indices decrease ≈ 6% (relative) from quiet Sun to bright plage.

IV. INTERPRETATION OF HYADES AND PLEIADES SPECTRA

A. Level of Ca II Emission Activity

Measurements of the cluster stars' Ca II emission are available from the Mount Wilson HK Project. Duncan et al. (1984) give data for the Hyades in the years 1981-1983. In the range 0.5 < B-V < 0.8 (0.6 < Hδ/Fe I < 1.2), the mean value for the Hyades stars observed both by Duncan et al. and by Rose was ⟨S⟩ = 0.34 ± 0.02. Older survey data for the Pleiades stars in the same color interval give $\langle S \rangle = 0.12$ larger than the Hyades stars. The relation between S and the Ca II H/Ca II K index defined by Rose (1984) appears linear for the Hyades stars, with a slope $\Delta S/[\Delta(\text{Ca II H/Ca II K})] \simeq -5 \pm 1.5$.

We can also deduce the mean Ca II emission for the particular stars that we have measured by using the solar relation between Ca II H/Ca II K and HK, $\Delta HK = -3.52\ \Delta(\text{Ca II H/Ca II K})$. From Rose (1984), $\Delta(\text{Ca II H/Ca II K}) = -0.061$ for the Hyades and -0.103 for the Pleiades, with respect to the field in the range $0.7 < \text{H}\delta/\text{Fe I} < 1.25$. Using $\langle S \rangle = 0.16$ for the field stars (Vaughan and Preston 1980), these imply $\langle S \rangle = 0.38$ for our Hyades stars, $\langle S \rangle = 0.52$ for our Pleiades stars. Both sets of data show that the cluster stars must have a large fraction of their surface area covered with bright plages. Further, the Pleiades are much more active than the Hyades, as Wilson (1963) first showed. The similarity of the S vs Ca II H/Ca II K relations suggests the stellar plages are similar to solar plages.

B. Hγ/G-band vs Hδ/Fe I

Figure 4a shows the Hγ/G-band vs Hδ/Fe I plot for field, Hyades, and Pleiades dwarfs. In Figure 4b the mean relation for the field dwarfs is removed, and the difference from that relation plotted. Both clusters deviate from the field stars. Metal abundance is not a cause of this deviation, since Rose (1984) demonstrated that field stars covering a wide range in composition all lie on a single line.

Also plotted in Figures 4a and 4b is a trajectory representing the range of variation of these line ratios in the solar data. The starting point is the measured position of the Sun, determined from the asteroid spectra. The measured values for the Sun in the system of Rose (1984) are given in Table II. The direction and magnitude are from the solar data over the range $0.18 < HK < 0.6$. Clearly, the direction and magnitude of the plage-induced line ratio variation is correct for explaining the cluster stars' spectral anomalies.

The lack of a difference between the Pleiades and Hyades in Hγ/G-band simply reflects the "saturation" of that ratio at high values of HK that was noted for the solar plage data in section IIID. If stars of much greater HK emission, comparable to solar flares, were observed, we would expect both Hγ/G-band and Hδ/Fe I to increase because the Balmer lines will out-brighten the metal lines. Thus, if the activity level on a field dwarf were monotonically increased, we would expect its trajectory in Figure 5a to first be down to the Hyades-Pleiades position, then toward the upper right, parallel to and within the cluster sequence. Three stars of extreme HK emission, $S > 0.5$, are plotted in Figure 4a, and they do lie in the cluster sequence.

According to the discussion in section III, the Hγ/G-band index is substantially more affected by plages than Hγ/4325. Hence one would expect to see a smaller deviation of the Hyades and Pleiades from normal field stars in the Hγ/4325 vs Hδ/Fe I diagram than in the Hγ/G-band vs Hδ/Fe I diagram. A comparison of Figures 4 and 5 reveals exactly this behavior. In Figure 5a is plotted Hγ/4325 vs Hδ/Fe I for field, Hyades, and Pleiades dwarfs; in Fig. 5b the mean relation for the field dwarfs is removed, and the difference from that relation plotted. Here again it was found in Rose (1984) that field stars, regardless of metal abundance, form a single mean relation in this diagram. Clearly the Hyades and Pleiades are substantially less deviant in the Hγ/4325 index, and their displacement is in reasonable accord with the trajectory representing the range of variation of the solar plage data. Furthermore, the location of the Hyades, Pleiades, and extremely active stars on a unique line in Figure 5 indicates a "saturation" of the Hγ/4325 index at high activity levels, a result that was anticipated by the solar data.

C. Surface Gravity

Our primary indicator of surface gravity is the ratio Sr II λ4077/Fe I λ4063. Figure 6 shows this ratio in plages as a function of HK emission index. The total range of variation is <1%. Thus, the presence of plages on a star will not disturb the measurement of the surface gravity.

In Figure 7 the measured differences of Sr II/Fe I are plotted against Hδ/Fe I for dwarfs in the Hyades, and in the Pleiades, compared to field stars with [Fe/H] > -0.75. (In Rose 1984 it was found that very metal-poor dwarfs are slightly displaced with respect to solar-abundance dwarfs.) It is clear that the Hyades stars do not deviate on average from the field relation and have normal surface gravities at our level of accuracy (0.1 in log g).

Stars of extreme HK emission will have much stronger brightening in the Balmer lines than in the metal lines. We expect them to appear to the right of the normal stars in Figure 7 as the Hδ line brightens. The extreme emission stars are plotted on Figure 7 and lie where expected. Strictly on the basis of Sr II/Fe I, these stars would be misclassified as subgiants.

The Pleiades are slightly offset in the Sr II/Fe I plot, by -0.015 (or -0.03 if the two extremely active stars #250 and #296 are included). This is a larger shift than even the brightest solar plage. The most reasonable interpretation of this offset is that plages on the Pleiades stars have surface brightnesses that exceed the brightest solar plages. At high Ca II surface brightness, Hδ will brighten, shifting the star to the right in Figure 7. Given the low sensitivity of Sr II/Fe I to changes in Ca II HK, and the examples of the extreme emission stars, this interpretation is clearly indicated. To our knowledge this is the first direct evidence that stellar plages may differ from solar plages in their surface brightness and not merely in the fraction of the star's surface area that the plages occupy.

D. Metallicity

Figure 8 plots the CN index p(3912)/p(CN) for the field and cluster stars, as functions of Hδ/Fe I. The trajectory for solar plages is also shown. The λ3886/λ3859 CN indicator shows similar effects and is not plotted here.

Based on their HK emission and the solar data of Figure 3, the Hyades ought to be shifted by the plage emission an amount equivalent to −0.2 in [Fe/H], and the Pleiades by −0.4 in [Fe/H]. Since the Hyades lie on the curve of [Fe/H] of −0.1 and the Pleiades on [Fe/H] = −0.5, we deduce metallicities of +0.1 for the Hyades and −0.1 for the Pleiades. The extreme emission stars are also plotted and clearly appear to have low metallicity; with correction for their emission, their metal abundance is solar. For comparison, Nissen (1980) gives [Fe/H] of 0.1 for the Hyades and 0.0 for the Pleiades, from photometric determinations.

V. COLOR INDICES OF THE HYADES

Campbell (1984) has shown the Hyades stars to be anomalous, compared to field stars, in two-color diagrams. The sense of the anomaly is that for stars of equal (V-K) index, the Hyades show smaller values of (B-V). Campbell interprets this difference as the result of dark star spots. The cool spots effectively have no emission in the B and V bands, but do contribute light in the K band. Thus the (B-V) index for each star would be normal, but (V-K) would be too large.

Excess emission from magnetic plages produces a color anomaly of the same sense. The plage emission is small in the V and K bands, but larger in the B band. Thus the (V-K) index is normal, but (B-V) is too small, just as Campbell has noted. Unfortunately, good data on plage contrast is not available in the K band, so a quantitative argument cannot be made.

Crawford (1969) originally showed such anomalies in the Stromgren uvby bands. Solar data is available in these short wavelength bands, and we will focus on the c_1 and m_1 indices (see Table III). Chapman and McGuire (1977) have shown that the contrast of plages observed in photometric passbands over the range $\lambda 4350$ Å to $\lambda 10100$ Å can be represented as an inverse power of the wavelength. We assume that over the range $\lambda 3500$-$\lambda 5500$ a power law relation will hold. If the index of the power law is z, then the plage-induced change in a difference of color indices, $(m_1 - m_2) - (m_2 - m_3)$, is proportional to 2.5 log $[(\lambda_2{}^2/\lambda_1\lambda_3)^{-z}]$. Substituting the wavelengths of the Stromgren passbands gives the result $\Delta c_1 = -1.08\ \Delta m_1$. Giampapa, Worden, and Gilliam (1979) have measured a mean value for solar plages of $\Delta m_1 = -0.03$. We estimate that the plages they measured had a mean HK value of $\approx 0.3 \pm 0.05$, with allowance for their 1' x 1' field of view. We thus deduce that the Hyades should have Stromgren offsets compared to the field of $\Delta c_1 = +0.03 \pm 0.01$ and $\Delta m_1 = -0.03 \pm 0.01$, caused by plage emission.

The magnitude of the spot effects on color indices can be calculated for the Hyades and Pleiades. From solar irradiance measures, we know the mean level of spot area coverage is about equal to its variance (Hudson and Willson 1981). The variance of stellar flux in the V band is ≈1% in the Hyades and ≈2% in the Pleiades (Radick et al. 1982, 1983). We assume these numbers correspond to the mean spot umbral area fraction. Using the contrast of sunspots given by Allen (1976), we infer c_1 and m_1 indices that are offset by $+7 \times 10^{-5}$, $+4 \times 10^{-3}$ in the Hyades and by twice as much in the Pleiades, due to star spots. (The differences between these values and Campbell's are not simply explained by his use of an area 5 times larger.)

The radiative flux blocked by star spots will be released over the Kelvin-Helmholtz time scale of the convection zone (Spruit 1981), about 2×10^5 yr for the Sun. We assume the level of spot activity on stars remains constant over this time. The stored flux will be radiated largely through an <u>increased temperature</u> of the unspotted photosphere. The stellar radius (and surface gravity) will not significantly change (Spruit 1981). This is contrary to Campbell's assumption.

A further point is that a substantial fraction of the flux blocked by spots is radiated within a few months by plage emission. Campbell argues that the color offsets must be caused by spots because the flux variance is so caused. This argument is not obviously true on the Sun. The variance of the solar irradiance on short time scales is caused by spots (Hudson and Willson 1981) as rotation carries them across the visible disk. The mean irradiance deficit of spots may be balanced, however, by emission from longer-lived, more widely distributed plages (Oster, Schatten, and Sofia 1982; Bruning and LaBonte 1983). The more uniform distribution of plages reduces their contribution to brightness variation. The presence of plages produces an elevated intensity from which the spot-induced decreases occur. Thus the Sun is not obviously dimmer, or redder, on average, simply because spots are present. Since the stored energy is reduced by plage emission, the radius and temperature changes of the star over the Kelvin-Helmholtz time will also be reduced.

We compute the change in stellar radius by using Spruit's equation (20) and assuming (1) the depth of the solar convection zone is 0.3 solar radii, and (2) 0.5 of the spot blocked flux is emitted by plages contemporary with the spots. We find the radius of a spotted star is 0.04 f larger than an equivalent unspotted star, where f is the flux fraction blocked by spots. For 1% umbral area, $f = 0.02$. This produces a surface gravity induced change of $\Delta c_1 = +2 \times 10^{-4}$, using $\partial c_1/\partial \log g$ from Stromgren et al. (1982).

Since the blocked flux is reemitted by a higher temperature photosphere, we calculate the temperature change under assumption (2) from above and find $\Delta T/T = f/4$. Using Campbell's value for $\partial(B-V)/\partial\theta$ and Crawford's (1975) for $\partial c_1/\partial(B-V)$ and $\partial m_1/\partial(B-V)$, we find $\Delta c_1 = +2.6 \times 10^{-3}$, $\Delta m_1 = -1.4 \times 10^{-3}$ for the Hyades.

The results of the above discussion are summarized in Table III. There it is seen that plage emission produces at least an order of magnitude larger effect on the c_1 index than any other effect, including spots. In short, plages appear to be responsible for the ~0.035 mag c_1 excess observed in Hyades F dwarfs.

V. ACTIVITY IN OTHER CLUSTERS

Our analysis predicts that color and spectral anomalies should be seen in any cluster whose stars exhibit enhanced Ca II H- and K-line emission. In some spectral indicator pairs, like Hγ/G-band vs Hδ/Fe I, the effects of plage emission "saturate," and all active stars share a sequence displaced from the field sequence. Other spectral indicator pairs, like Sr II/Fe I vs Hδ/Fe I, show anomalies only for stars with active region surface brightnesses that exceed the range of solar plages.

A. Pleiades

As we have shown, the Pleiades do share the spectral anomalies of the Hyades. Further, the Pleiades, with higher average Ca II emission than the Hyades, show an anomaly in Sr II/Fe I vs Hδ/Fe I (Fig. 7). We are thus able to conclude that active stars in the Pleiades differ from the Sun not only in the fraction of their area covered by plage, but also in their plage brightness.

The issue of area coverage and surface brightness is not a trivial one, as our inability to resolve the disks of stars forces us to measure only the integrated area-brightness product. As we state in section IIA, the integrated Ca II HK emission for normal stars, even in the Pleiades, does not exceed the largest values of HK seen in solar plages. Thus, the Ca II data alone do not prove that stars have plages of intrinsically higher surface brightness; they may only have larger fractions of their area covered by plages of solar intensity. Wolff, Heasley, and Timothy (1983) were able to show from the Ca II data alone that plages on active stars must occur over large fractions of the stellar surface, at least to latitudes ±25°. They also deduced that compared with the Sun, active stars likely have a larger number of discrete active regions.

Our finding that the Pleiades stars have plages exceeding the brightest solar plages adds a new dimension to the nature of activity on solar-type stars. Stars that have integrated Ca II emission of reasonable value (not extreme stars) and that obey all the other normal spectral relations may be expected to be good solar analogs. When these stars have a large area covered with plage, this reflects a larger number of active regions produced by the stellar dynamo (Wolff et al. 1983). The dynamo action is presumably enhanced if the star rotates at higher velocity than the Sun, as active cluster stars do (Kraft 1967).

For individual plages on a star to exceed solar plage brightness, the rate of heating per unit area must exceed solar levels. The brightest solar plages occur in emerging flux regions, where new magnetic flux is erupting to the surface (e.g., Zirin 1974). The faintest "plages" are pieces of the chromospheric network, which is the debris from the decay of active regions. On the Sun, it is not clear whether the Ca II brightness is proportional to the magnetic field strength or the rate of charge of magnetic flux, or inversely related to the time since the field erupted to the surface; all three are highly correlated. Further, flare energy release will exceed the static heating, raising the plage brightness above its normal value. In general, the plage brightness is related to complexity and speed of processes that move magnetic flux on the surface. Thus the surface brightness of plage measures a different property of the star than the surface area coverage measures. Simple velocity "turbulence" is probably not the determining factor. Soderblom (1982) finds that atmospheric turbulence does not significantly vary with stellar age or rotation.

Color anomalies should be difficult to detect in the Pleiades. Differences in intracluster dust reddening will mask any observable effects. Measurements of the time variations of the colors of Pleiades stars (Radick et al. 1982) might be able to discriminate spot and plage contributions, but would require even higher precision than that now obtained.

B. Praesepe and Coma

Crawford and Barnes (1969) demonstrated that Praesepe stars show the same color anomalies as the Hyades stars. Praesepe is known to have an age and Ca II emission level about equal to the Hyades (Wilson 1963). The Coma cluster does not share the Hyades anomalies in Stromgren colors (Crawford 1975). Its age and activity level also are about equal to the Hyades (Barry, Hege, and Cromwell 1984), and thus Coma represents a serious discrepancy from our basic prediction.

We have not obtained observations of a significant number of Praesepe or Coma stars. Once the data is available, the various spectral indicators can be compared with the field and Hyades stars. One problem will be the sparseness of Coma, with only a few members in the spectral classes F to K.

We can note a relation from Barry's (1974) study of the Hyades anomaly. He found that for the four clusters, Hyades, Praesepe, Coma, and α Persei, a mean relation $\delta c_1 \simeq -2\delta\ m_1$. This relation between the colors is in the correct sense of our prediction for plage (sec. IV), but of larger amplitude. Since these clusters have nearly equal Ca II emission, we expect no difference in the plage-induced δc_1 among them. Now, if Barry's relation describes a pure metallicity effect, as he claimed, then the measurement of δc_1, as an activity indicator must be made relative to a population of the same metallicity. Comparison of the Hyades and Coma is not then appropriate.

VI. CONCLUSIONS

In summary, excess plage emission provides an attractive explanation for the spectral anomalies in the Hyades reported by Rose (1984). The solar plage indices reproduce the observed displacement of the Hyades relative to normal field stars in several diagnostic diagrams. In addition, the leveling off in the Hγ/G-band and Hγ/4325 indices observed in the strongest solar plages appears to be manifested in the lack of a displacement between the Hyades and stars with stronger chromospheric activity (e.g., the Pleiades). Furthermore, our analysis supports the conclusion of Campbell (1984) that the observed photometric color anomalies in the Hyades relative to field stars are the result of surface activity on the former, but indicates that excess plage emission, rather than spots, readily explains the observations. Further, spots cannot cause the observed spectrum line anomalies; to first approximation the spot atmosphere acts as a cool "companion" and would move the star along the dwarf sequence of the normal field stars. Finally, the small observed displacement between the Hyades and Pleiades in the Sr II/Fe I vs Hδ/Fe I diagram and the larger displacement between the Hyades and extremely active stars indicates that at some point the observed displacements are no longer explained simply as an increased filling factor of solar-like plages.

Given that unevolved main-sequence F stars in the Hyades exhibit a c_1 excess, some caution must be used in deriving the age of a star from from its location in the c_1, b-y diagram (e.g., Twarog 1980). In particular, since plage activity produces a c_1 excess, young, active stars may be mistaken for older, partially evolved stars.

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TABLE I

Solar Line Ratios

Line ratio	Mean quiet Sun value (HK < 0.22)	Fitted line
Hα/Fe I	0.644	0.612 + 0.115 HK (HK > 0.22)
Hβ/Fe I	0.710	0.680 + 0.0825 HK (HK > 0.22)
Hγ/Fe I	0.872	0.882 − 0.05 HK (HK < 0.4)
Hδ/Fe I	0.787	0.779 + 0.039 HK
Hγ/G-band	1.150	1.198 − 0.240 HK (HK < 0.45)
p(3912)/p(CN)	1.229	1.262 − 0.177 HK
λ3886/λ3859	0.983	1.009 − 0.137 HK
Sr II/Fe I	1.025	1.028 − 0.0174 HK
Ca II H/K	1.190	1.242 − 0.284 HK

TABLE II

Sun Measured as a Star

Line ratio	Mean value	Error of a measure
Hδ/Fe I	0.910	0.006
Hγ/4325	0.925	0.010
Hγ/G-band	1.16	0.009
$\lambda 3912/\langle \mathrm{CN} \rangle$	1.38	0.009
$\lambda 3886/\lambda 3859$	1.15	0.010
Sr II/Fe I	1.096	0.006
Ca II H/Ca II K	1.16	0.016

TABLE III

Changes in Stromgren Indices in Hyades

Cause	Δc_1	Δm_1
Observed plage	+0.03	-0.03
Observed spots	+0.00007	+0.004
Inferred gravity change	+0.0002	—
Inferred temperature change	+0.0026	-0.0014
Total	+0.033	-0.027

Calculations assume 1% umbral area, 5% penumbral area, 50% of spot blocked flux compensated by plage emission.

FIGURE CAPTIONS

Fig. 1—Balmer line to Fe I line ratios for solar regions. Regions with HK < 0.22 are nonmagnetic (quiet), with HK > 0.22 are magnetic (plage). Solid lines are based on Table I. (upper left) Hα/Fe I λ6593 Å, (upper right) Hβ/Fe I λ4892 Å, (lower left) Hγ/Fe I λ4325 Å, and (lower right) Hδ/Fe I λ4063 Å. The latter is an indicator of stellar surface temperature that shows little variation with magnetic activity.

Fig. 2—Hγ to G-band ratio for solar regions. This ratio varies more than Hγ/Fe I, but both level off for plages with HK > 0.5.

Fig. 3—CN indices for solar regions. Fitted lines listed in Table I. Top: "Continuum" peak at λ3912 Å ratioed to the average of peaks at λ3852, λ3864, and λ3876 Å. Bottom: λ3886 Fe I + H I ratioed to CN λ3859 Å band.

Fig. 4—Stellar Hγ/G-band vs Hδ/Fe I. (a) Measured values for dwarfs in the field, the Hyades, and the Pleiades. (b) Residuals from the mean relation for the field stars. Field stars o; Hyades X; Pleiades +. Stars of extreme Ca II emission $\boxed{+}$. The Sun is the filled circle, and the arrow is the range of solar regions, from quiet to bright plage (0.18 < HK < 0.6).

Fig. 5—Stellar Hγ/λ4325. Same format as Fig. 4.

Fig. 6—Sr II λ4077 Å/Fe I λ4063 Å for solar regions. This indicator of stellar surface gravity shows little variation with magnetic activity. Fitted line listed in Table I.

Fig. 7--Stellar Sr II/Fe I vs Hδ/Fe I. Same format as Fig. 4. Dashed line shows the mean relation for field giants. The Hyades stars are not offset from the field stars; their surface gravity is normal. Stars of extreme Ca II emission are offset to the subgiant region because of abnormal emission in Hδ compared to the metal lines. The Pleiades are slightly offset, implying their plages have higher surface brightness than the brightest solar plage.

Fig. 8--Stellar CN index. The Sun (•), Hyades (X), Pleiades (+), and extreme emission stars ($\boxed{+}$) are compared with curves of constant [Fe/H] derived from observations of field stars. Accounting for the effects of plage emission (Fig. 3), we find [Fe/H] = +0.2 for the Hyades, -0.1 for the Pleiades.

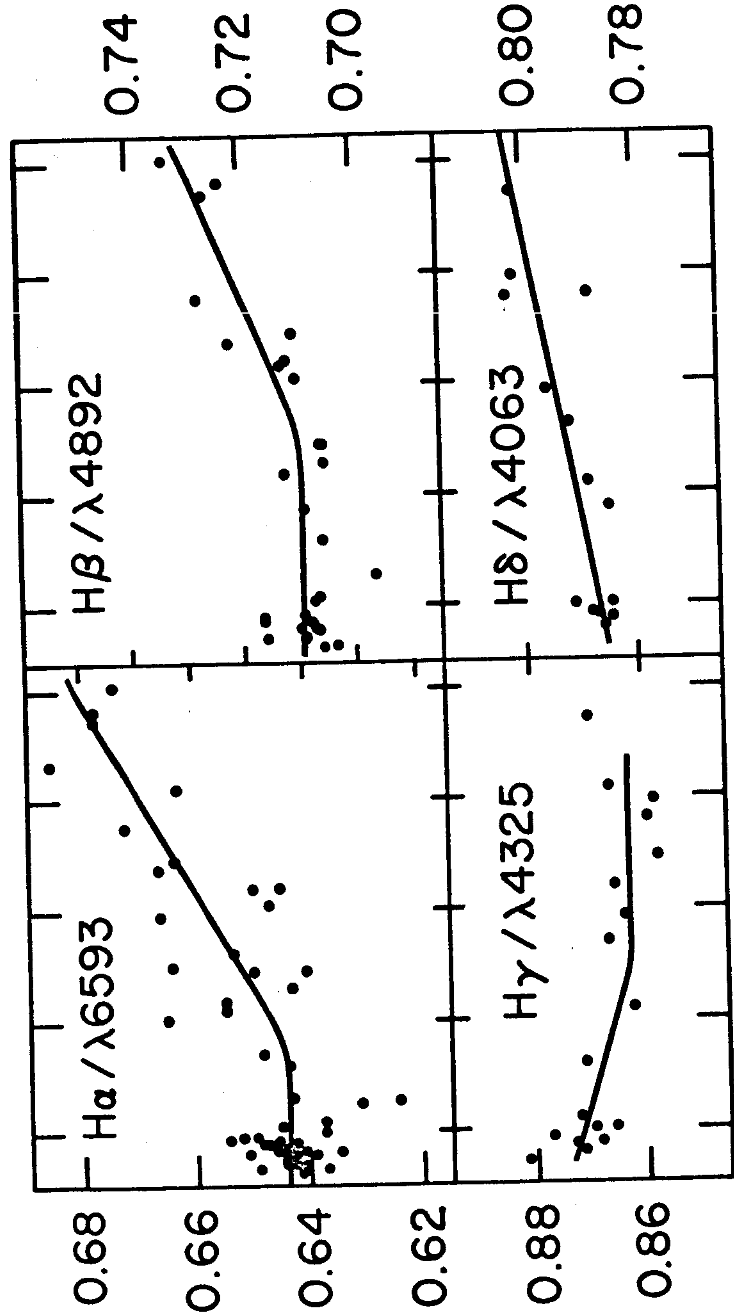
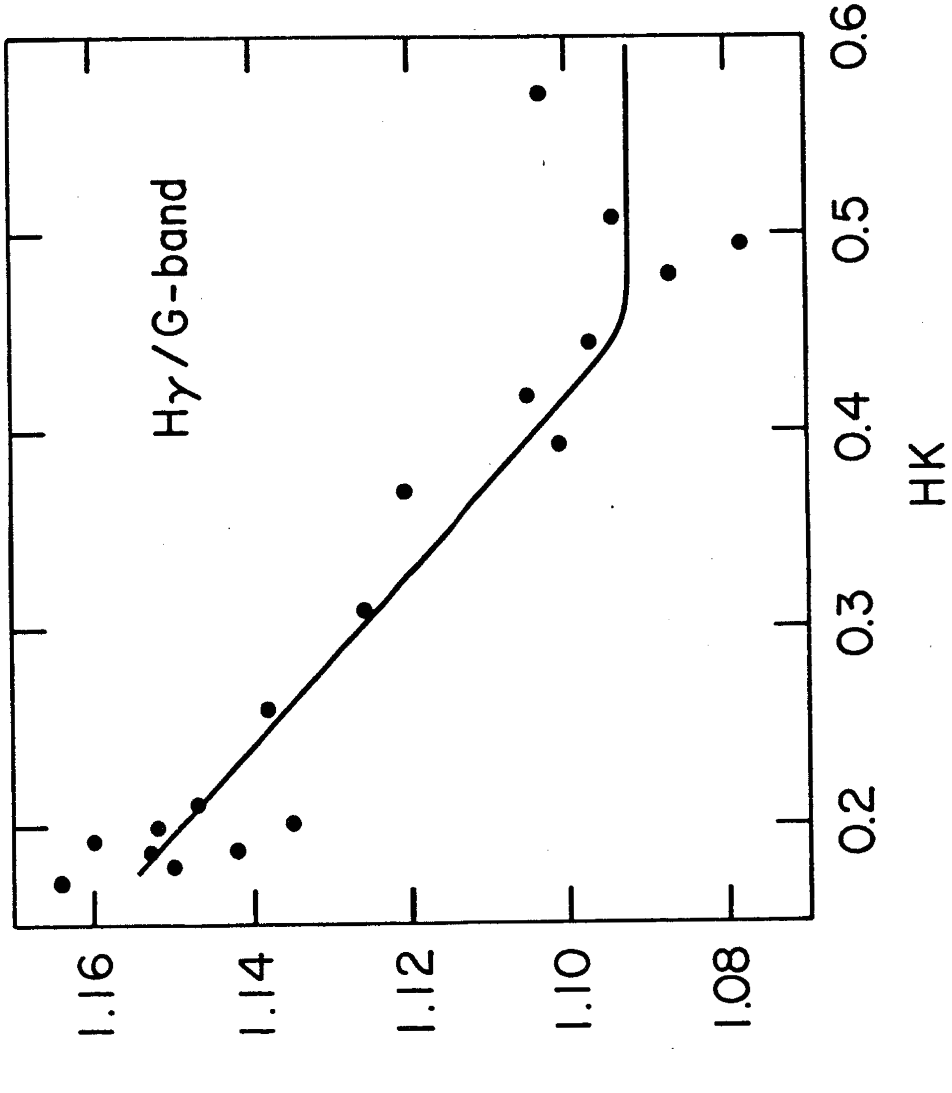


Figure 1
LaBonte &
Rose

Figure 2
LaBonte &
Rose



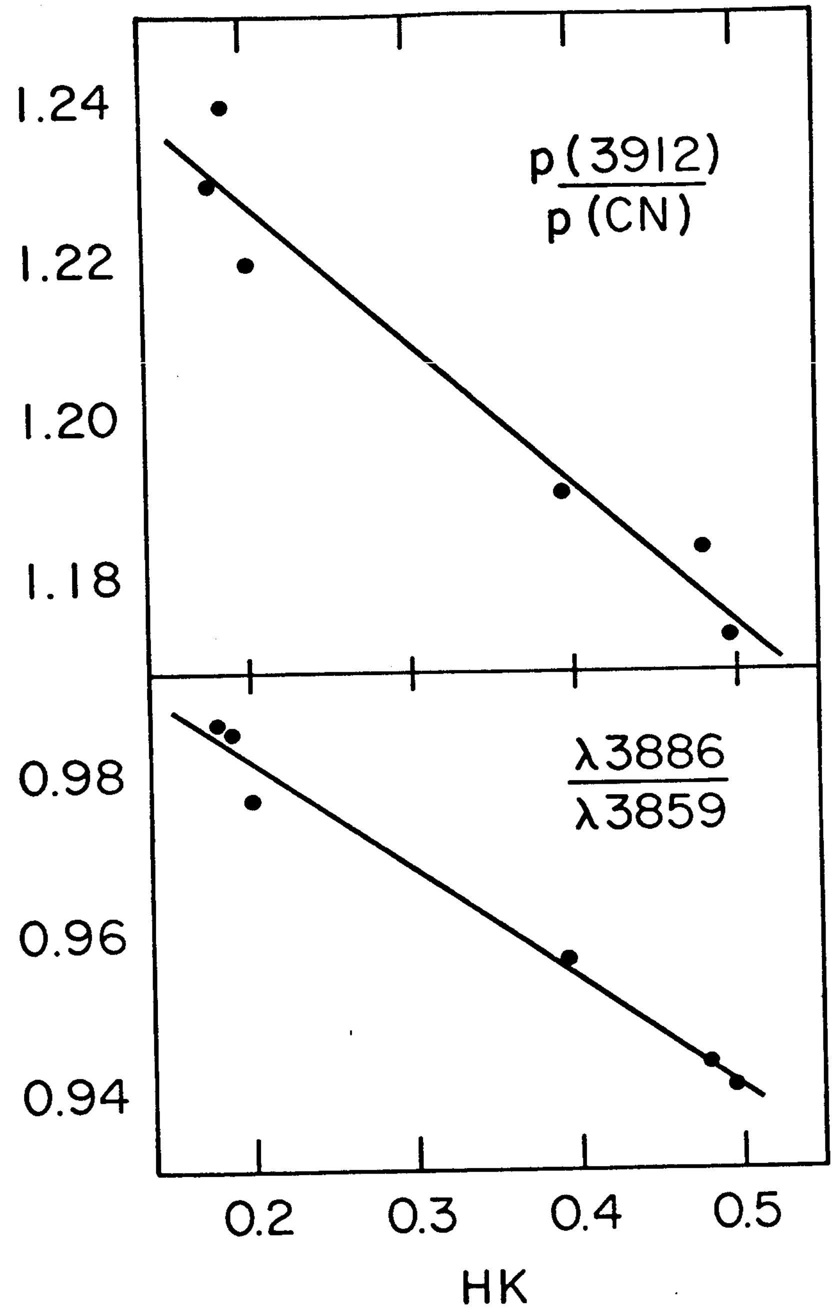


Figure 3.
LaBonte &
Rose.

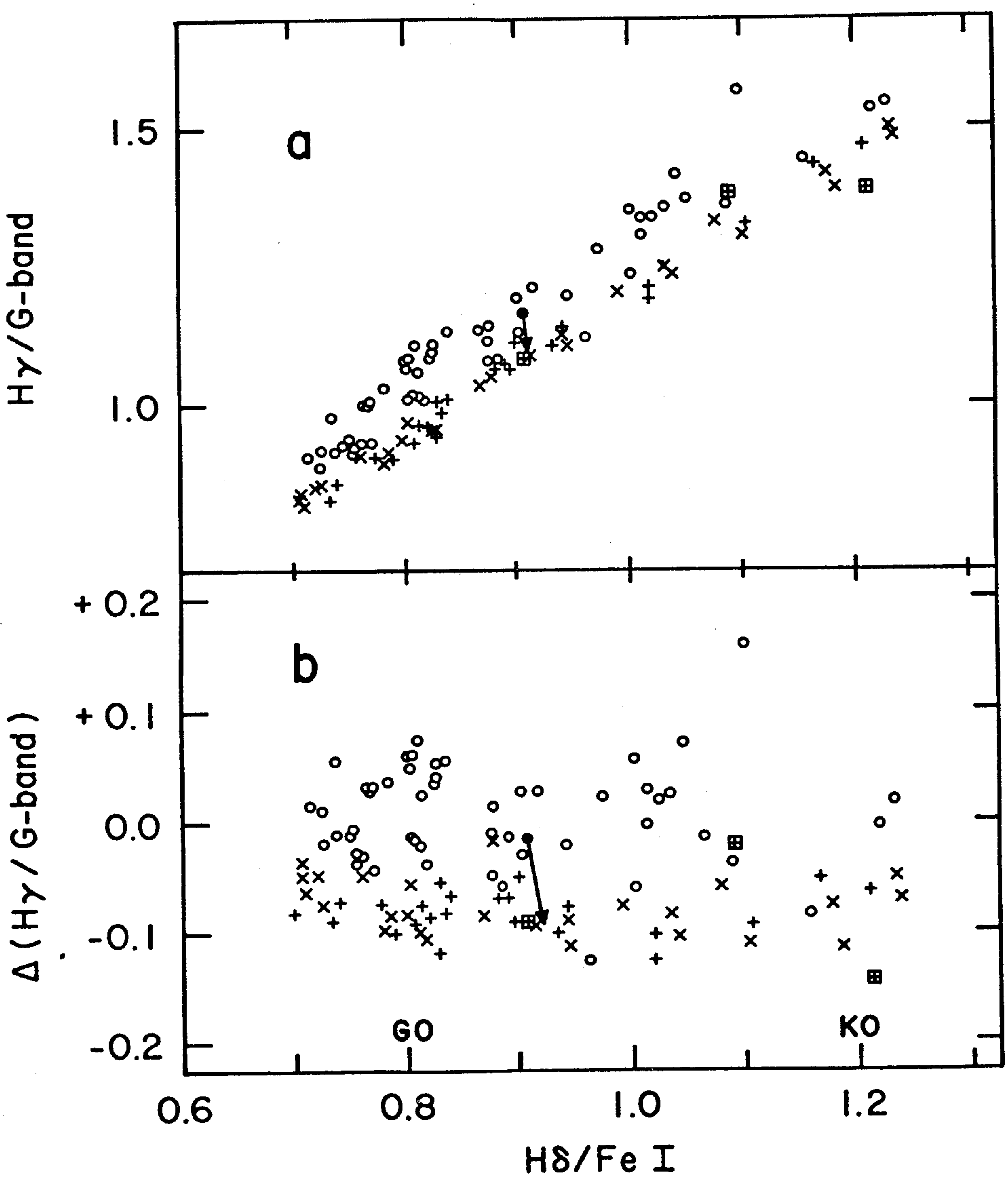


Figure 4
LaBonte &
Rose

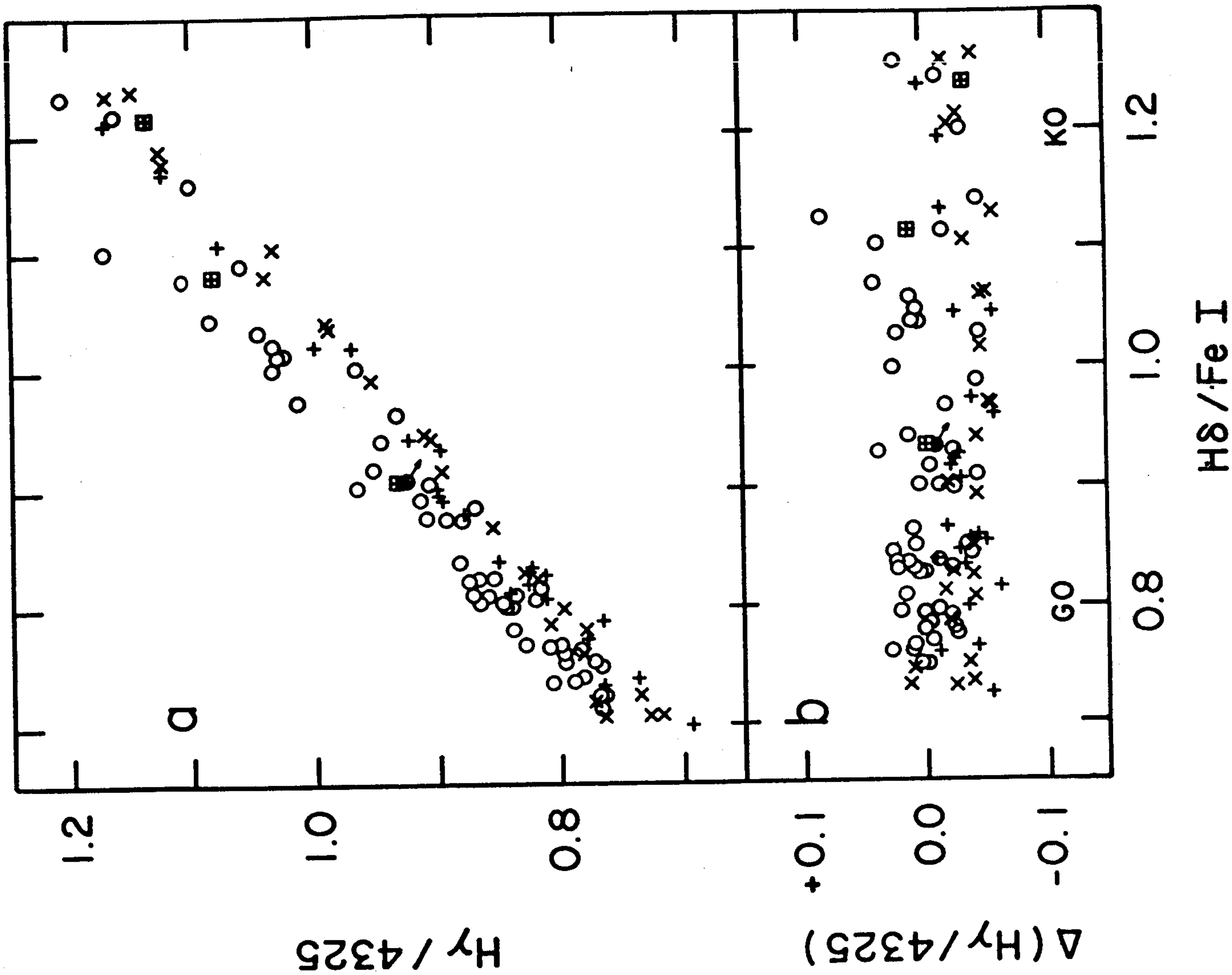


Figure 5
LaBonte and Rose

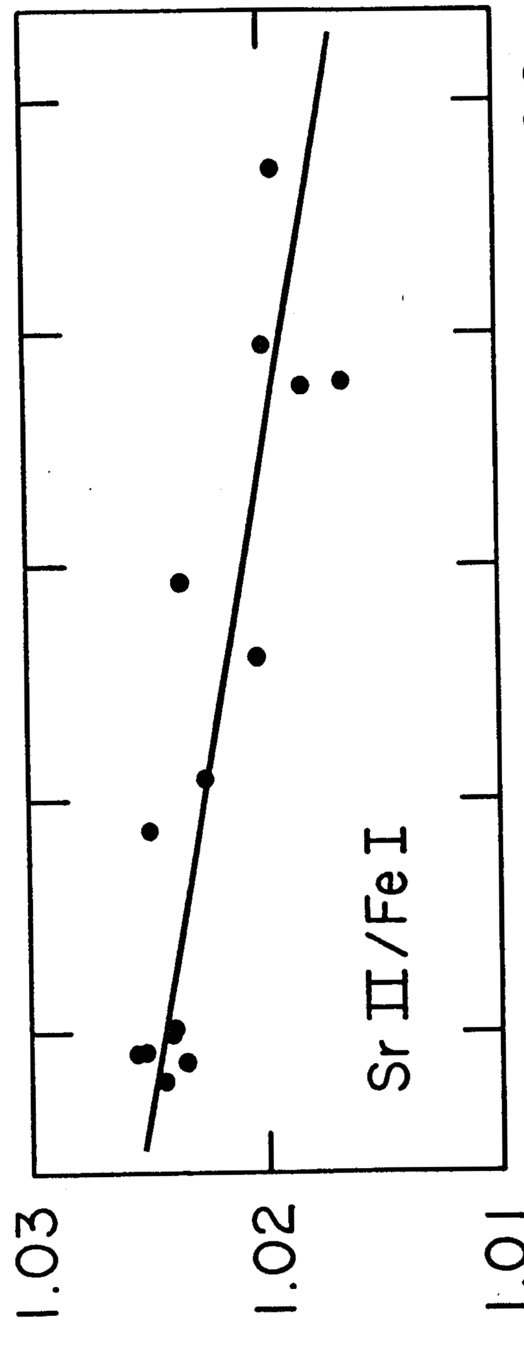


Figure 6 LaBonte & Rose

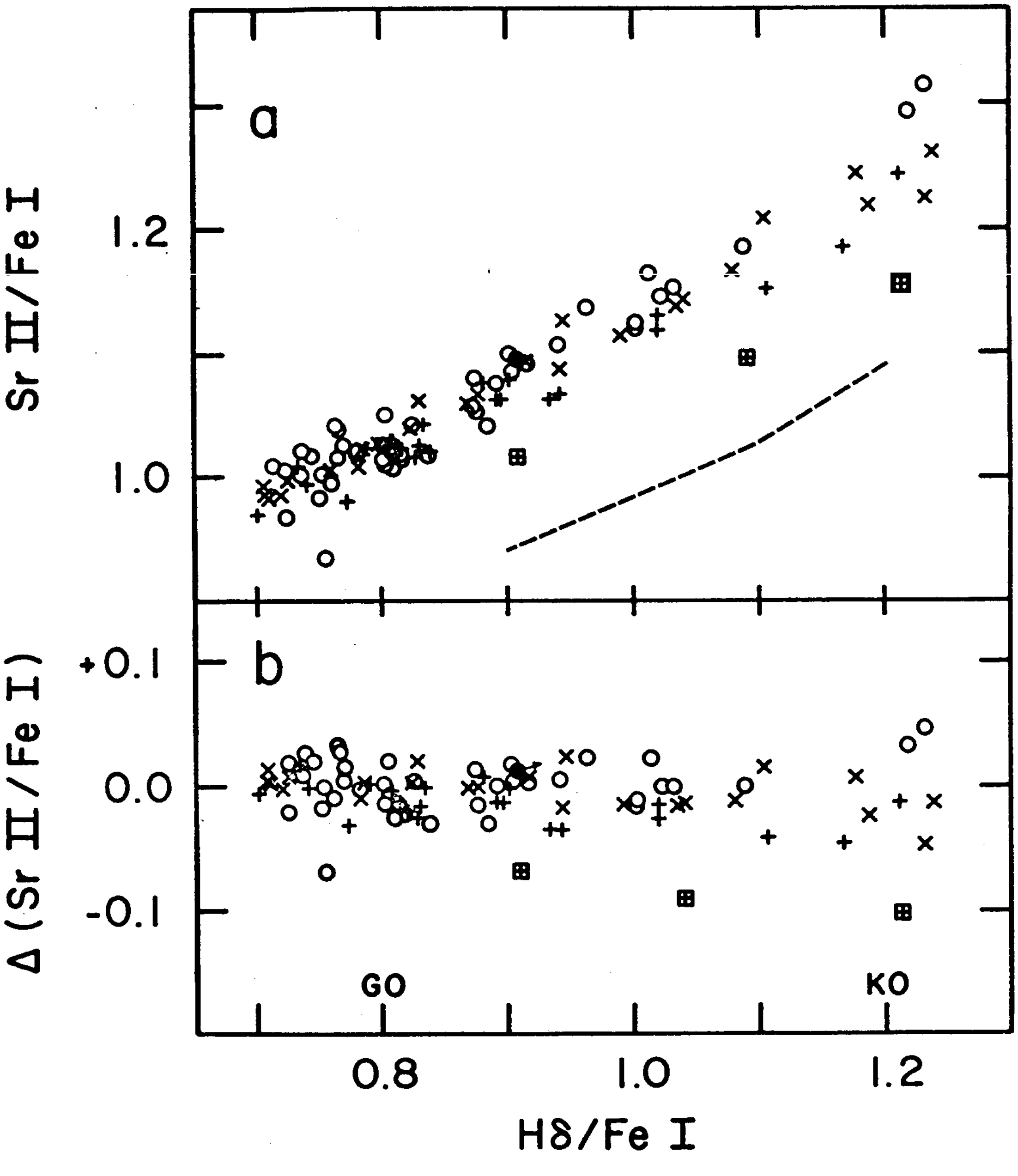


Figure 7
LaBonte &
Rose

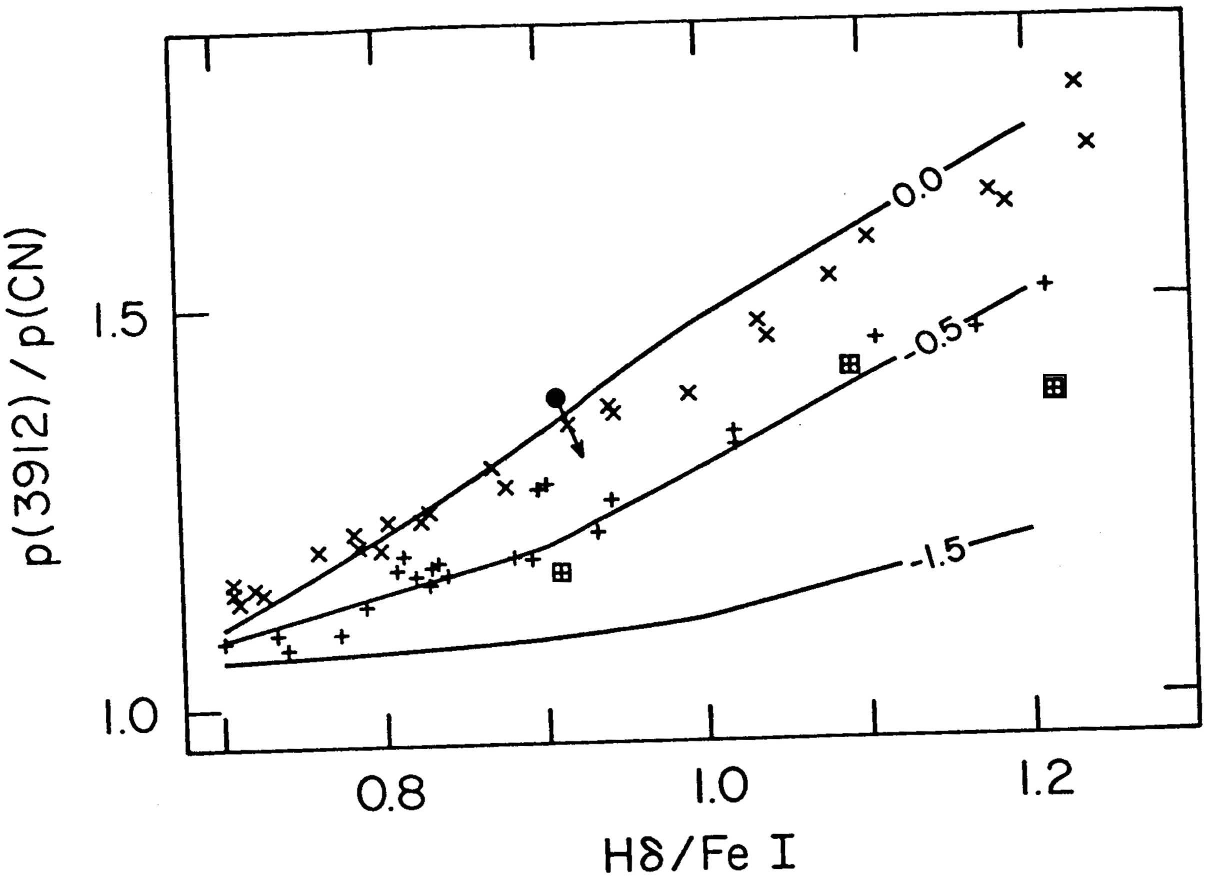


Figure 8
LaBonte & Rose